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(54) LED OUTPUT RESPONSE DAMPENING FOR IRRADIANCE STEP RESPONSE OUTPUT

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H05B 33/08 (2006.01)

(52) **U.S. Cl.**
CPC ***H05B 33/0809*** (2013.01); ***H05B 33/0845*** (2013.01)

(58) **Field of Classification Search**
USPC .... 315/185 R, 192, 224, 291, 297, 300, 315/299, 302, 307, 308, 311, 362
See application file for complete search history.

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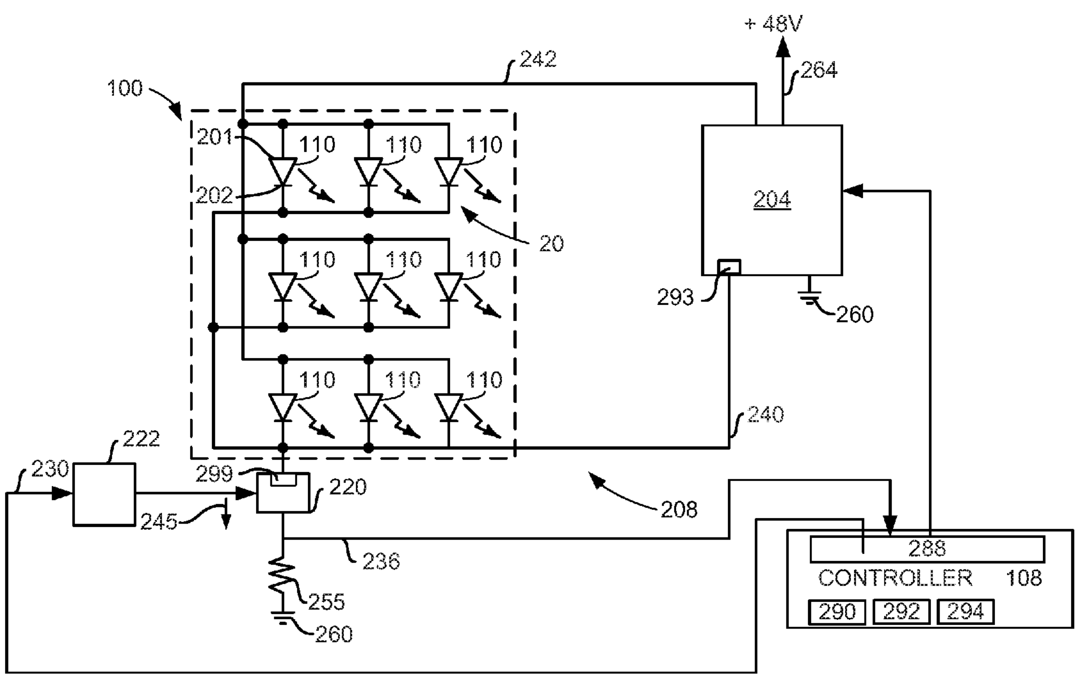
(57) **ABSTRACT**

A system and method for operating one or more light emitting devices is disclosed. In one example, the intensity of light provided by the one or more light emitting devices is adjusted responsive to follow a step change in requested lighting output.

18 Claims, 5 Drawing Sheets



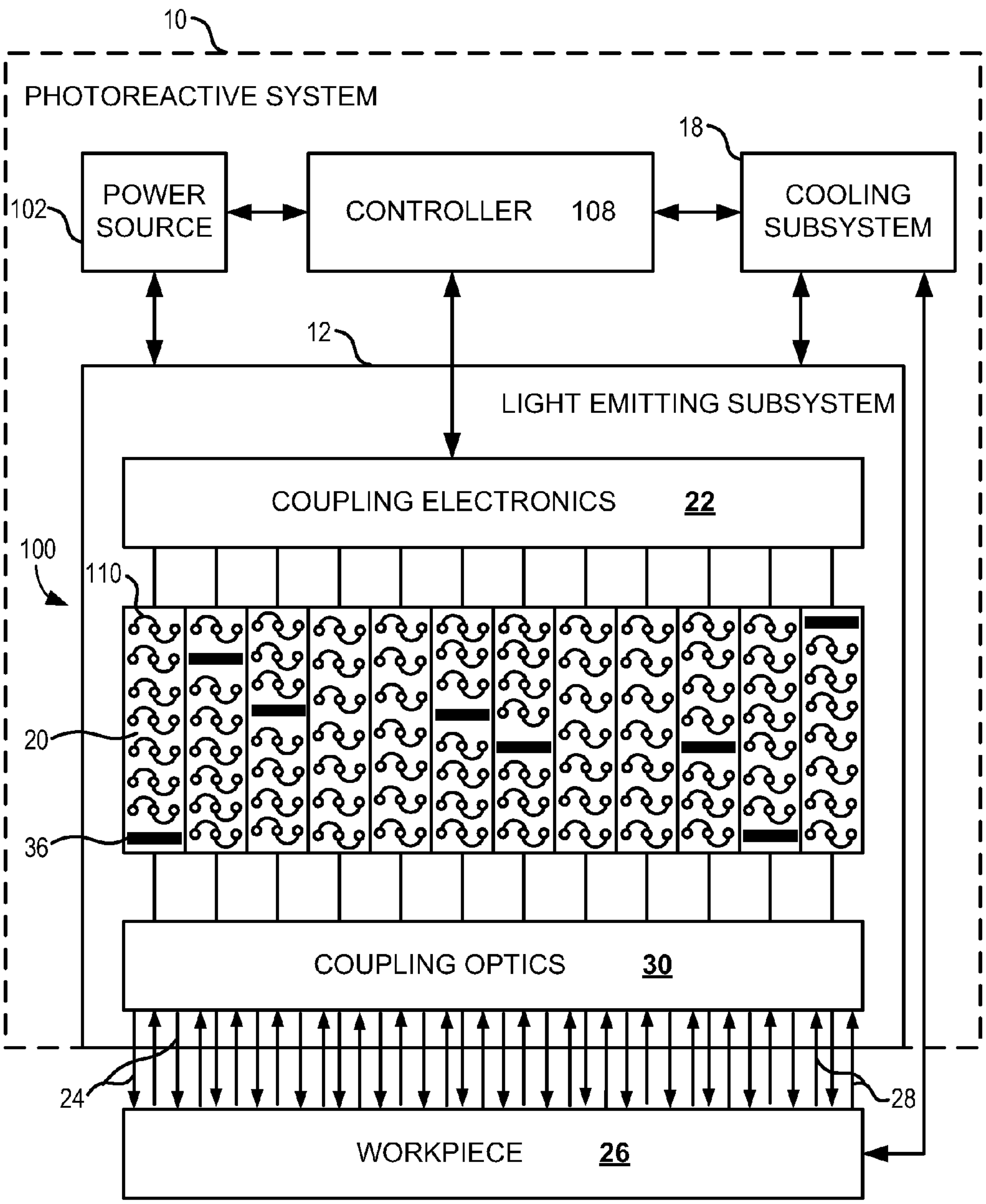
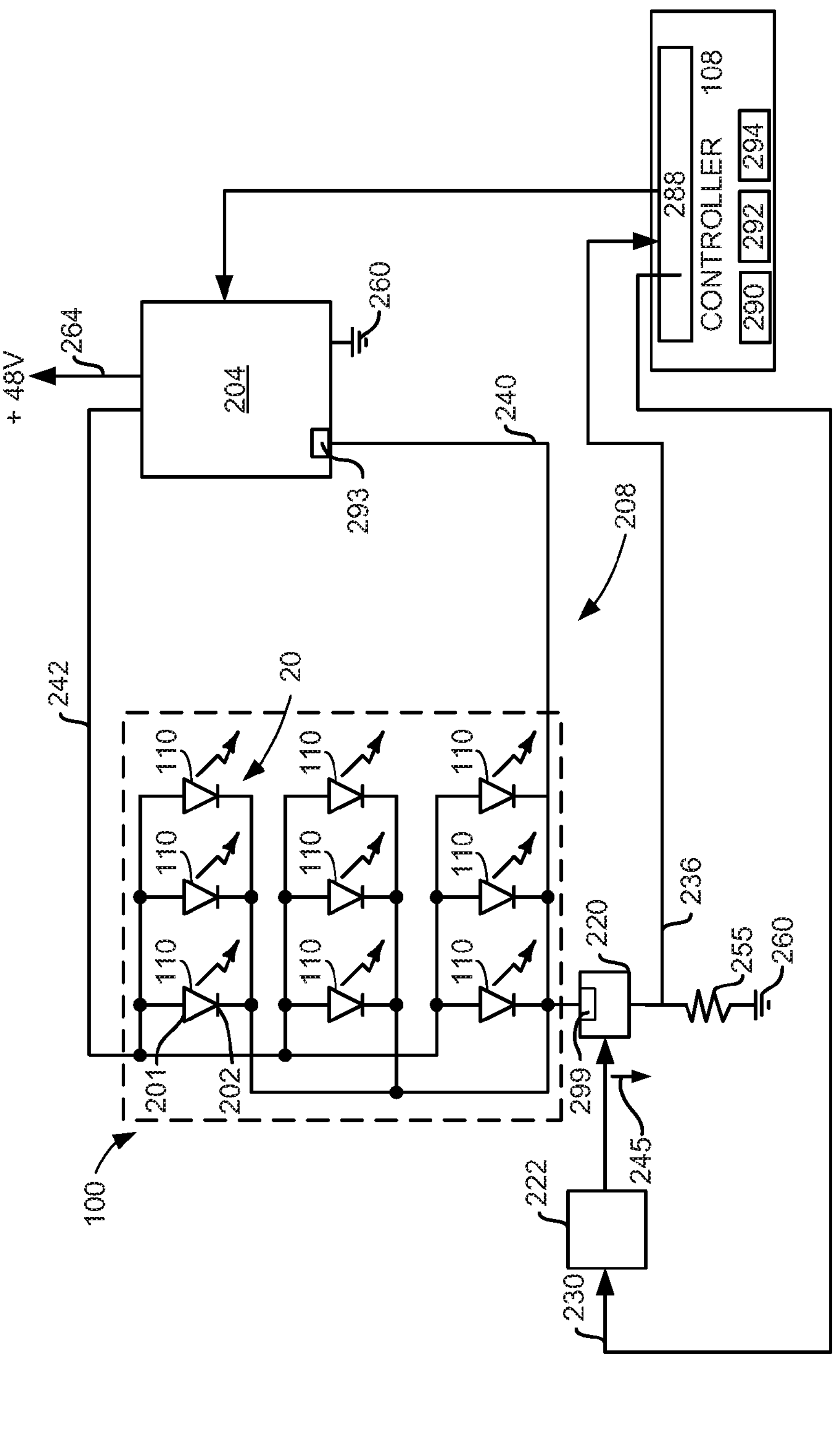
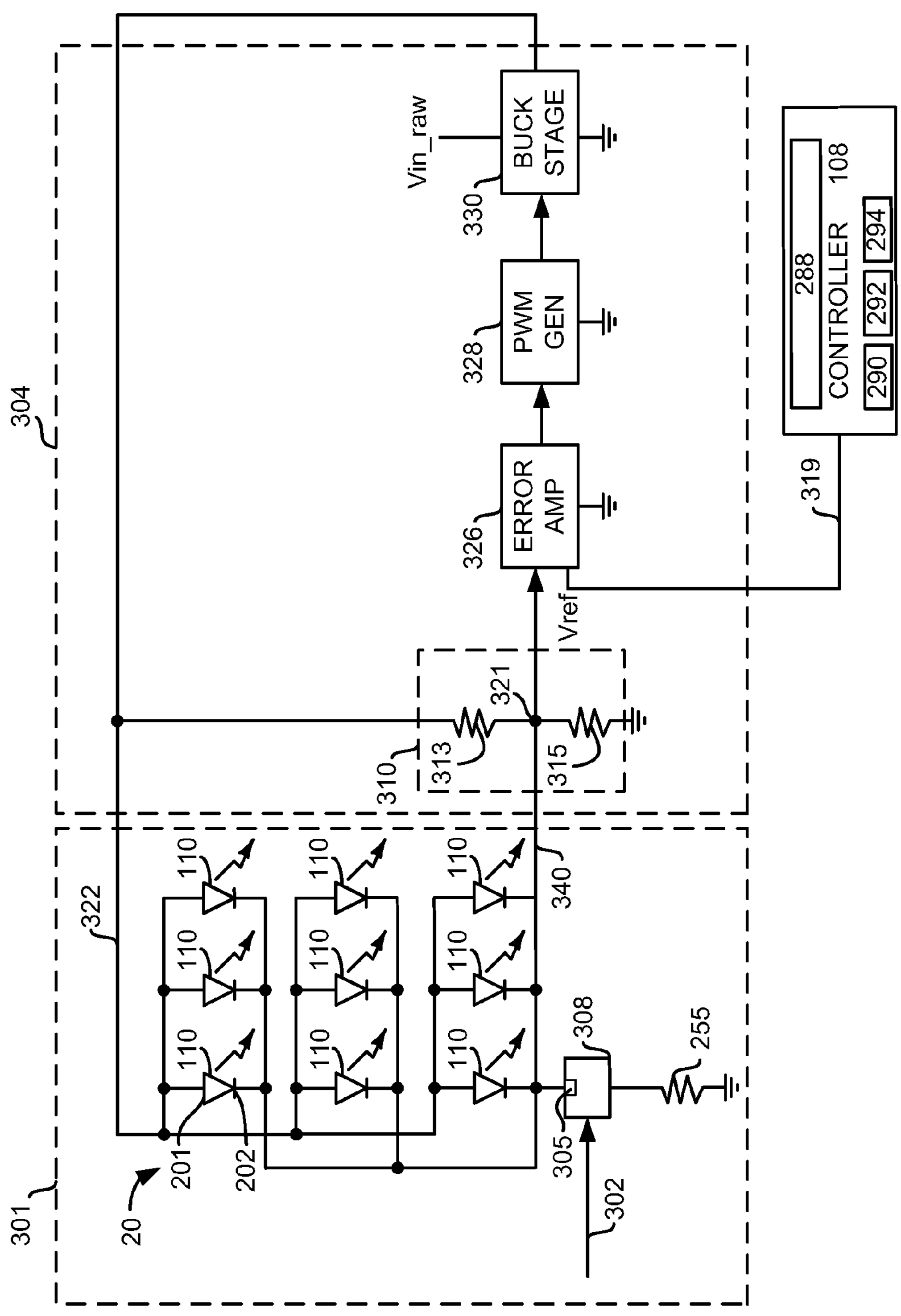

10
PHOTOREACTIVE SYSTEM
18
102
POWER SOURCE
CONTROLLER 108
COOLING SUBSYSTEM
12
LIGHT EMITTING SUBSYSTEM
COUPLING ELECTRONICS 22
100
110
20
36
COUPLING OPTICS 30
24
28
WORKPIECE 26

FIG. 1

FIG. 2

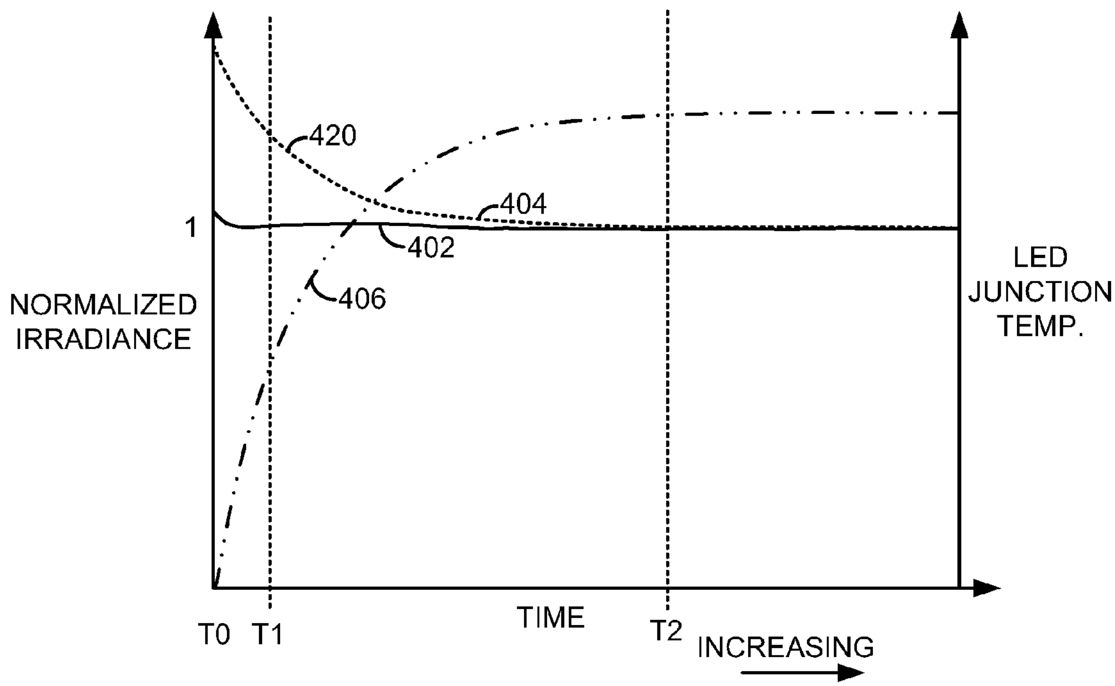


+ 48V
264
204
260
240
293
208
242
20
110
100
201
202
299
220
236
255
245
222
230
CONTROLLER
108
288
290
292
294



304
Vin_raw
BUCK STAGE
330
PWM GEN
328
ERROR AMP
326
CONTROLLER
108
288
290
292
294
319
Vref
321
310
313
315
301
322
110
340
308
255
20
201
202
305
302

FIG. 3



420
404
1
402
406
NORMALIZED
IRRADIANCE
LED
JUNCTION
TEMP.
T0
T1
TIME
T2
INCREASING

FIG. 4

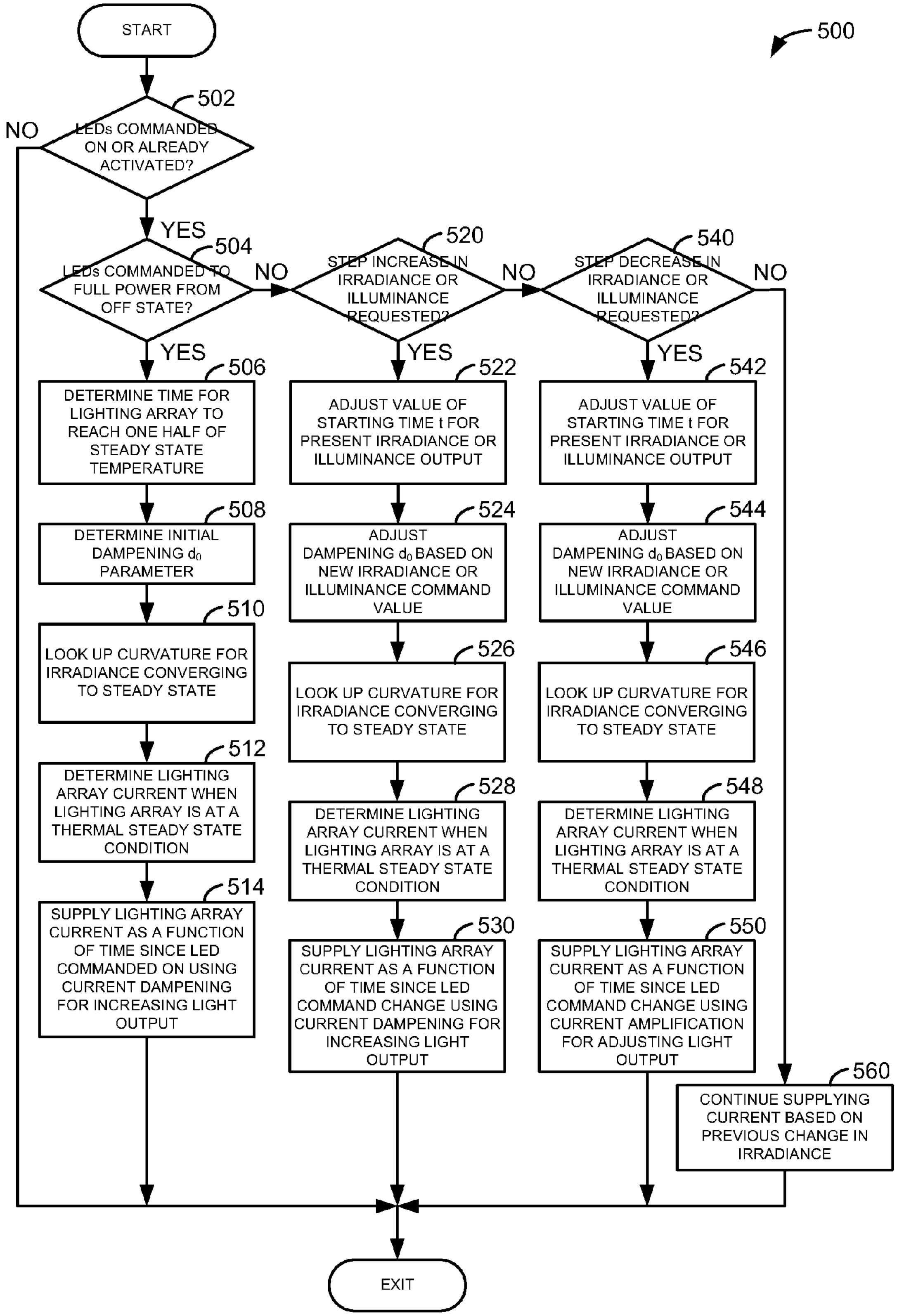

500
START
502
LEDs COMMANDED ON OR ALREADY ACTIVATED?
NO
YES
504
LEDs COMMANDED TO FULL POWER FROM OFF STATE?
NO
YES
506
DETERMINE TIME FOR LIGHTING ARRAY TO REACH ONE HALF OF STEADY STATE TEMPERATURE
508
DETERMINE INITIAL DAMPENING d_0 PARAMETER
510
LOOK UP CURVATURE FOR IRRADIANCE CONVERGING TO STEADY STATE
512
DETERMINE LIGHTING ARRAY CURRENT WHEN LIGHTING ARRAY IS AT A THERMAL STEADY STATE CONDITION
514
SUPPLY LIGHTING ARRAY CURRENT AS A FUNCTION OF TIME SINCE LED COMMANDED ON USING CURRENT DAMPENING FOR INCREASING LIGHT OUTPUT
520
STEP INCREASE IN IRRADIANCE OR ILLUMINANCE REQUESTED?
NO
YES
522
ADJUST VALUE OF STARTING TIME t FOR PRESENT IRRADIANCE OR ILLUMINANCE OUTPUT
524
ADJUST DAMPENING d_0 BASED ON NEW IRRADIANCE OR ILLUMINANCE COMMAND VALUE
526
LOOK UP CURVATURE FOR IRRADIANCE CONVERGING TO STEADY STATE
528
DETERMINE LIGHTING ARRAY CURRENT WHEN LIGHTING ARRAY IS AT A THERMAL STEADY STATE CONDITION
530
SUPPLY LIGHTING ARRAY CURRENT AS A FUNCTION OF TIME SINCE LED COMMAND CHANGE USING CURRENT DAMPENING FOR INCREASING LIGHT OUTPUT
540
STEP DECREASE IN IRRADIANCE OR ILLUMINANCE REQUESTED?
NO
YES
542
ADJUST VALUE OF STARTING TIME t FOR PRESENT IRRADIANCE OR ILLUMINANCE OUTPUT
544
ADJUST DAMPENING d_0 BASED ON NEW IRRADIANCE OR ILLUMINANCE COMMAND VALUE
546
LOOK UP CURVATURE FOR IRRADIANCE CONVERGING TO STEADY STATE
548
DETERMINE LIGHTING ARRAY CURRENT WHEN LIGHTING ARRAY IS AT A THERMAL STEADY STATE CONDITION
550
SUPPLY LIGHTING ARRAY CURRENT AS A FUNCTION OF TIME SINCE LED COMMAND CHANGE USING CURRENT AMPLIFICATION FOR ADJUSTING LIGHT OUTPUT
560
CONTINUE SUPPLYING CURRENT BASED ON PREVIOUS CHANGE IN IRRADIANCE
EXIT

FIG. 5

LED OUTPUT RESPONSE DAMPENING FOR IRRADIANCE STEP RESPONSE OUTPUT

FIELD

The present description relates to systems and methods for improving the irradiance and/or illuminance response of light-emitting diodes (LEDs). The methods and system may be particularly useful for lighting arrays that are commanded to output in a step-wise manner.

BACKGROUND/SUMMARY

Solid-state lighting devices have many uses in residential and commercial applications. Some types of solid-state lighting devices may include laser diodes and light-emitting diodes (LEDs). Ultraviolet (UV) solid-state lighting devices may be used to curing photo sensitive media such as coatings, including inks, adhesives, preservatives, etc. The curing time of photo sensitive media may be sensitive to the intensity of light directed at the photo sensitive media and/or the amount of time that the photo sensitive media is exposed to light from the solid-state lighting device. However, output of solid-state lighting devices may vary with device junction temperatures and other conditions such that it may be difficult to provide uniform output during the curing process. Consequently, it may be desirable to provide more consistent and uniform output from the lighting devices so that work piece curing time may be more precisely controlled.

The inventors herein have recognized the above-mentioned disadvantages and have developed a method for operating one or more light emitting devices, comprising: in response to a step change in requested output of the one or more light emitting devices, adjusting current supplied to the one or more light emitting devices responsive to one or more parameters based on output of the one or more light emitting devices when a step change in voltage or current is applied to the one or more light emitting devices, the step change in voltage or current not occurring at a same time as the step change in the requested output of the one or more light emitting devices.

By controlling current flow through a lighting array based on response of the lighting array when a step current or voltage is applied to the lighting array, it may be possible to more precisely follow a step request in lighting array output. Consequently, a more uniform output from the lighting array may be output during operation of the lighting array. For example, output of a lighting array may be more intense when the lighting array is initially activated in response to activating the lighting array. However, as time goes on after initial activation, output from the lighting array may decay and converge to a desired lighting array output. Parameters such as percent of irradiance overshoot initially relative to steady state irradiance output and time for the lighting array to reach half way to the steady state temperature light output when the lighting array is activated via a step change in voltage or current applied to the lighting array may be a basis for controlling current flow into the lighting array such that output of the lighting array (e.g., irradiance) approaches a step change in desired lighting array output. Thus, an unregulated response of a lighting array may be a basis for regulating output of a lighting array.

The present description may provide several advantages. Specifically, the approach may improve lighting system output consistency. Additionally, the approach may be provided without attempting to feedback lighting system output, thereby simplifying lighting array current control. Further still, the approach may be provided to both step increases and decreases in requested lighting system output.

The above advantages and other advantages, and features of the present description will be readily apparent from the following Detailed Description when taken alone or in connection with the accompanying drawings.

It should be understood that the summary above is provided to introduce in simplified form a selection of concepts that are further described in the detailed description. It is not meant to identify key or essential features of the claimed subject matter, the scope of which is defined uniquely by the claims that follow the detailed description. Furthermore, the claimed subject matter is not limited to implementations that solve any disadvantages noted above or in any part of this disclosure.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** shows a schematic depiction of a lighting system;

FIGS. **2-3** show schematics of example current regulating systems for the lighting system in FIG. **1**;

FIG. **4** shows a plot of an example simulated response of the lighting system shown in FIGS. **1-3**; and

FIG. **5** shows an example method for controlling output of a lighting system.

DETAILED DESCRIPTION

The present description is related to a lighting system with a plurality of electrical current output amounts. FIG. **1** shows one example lighting system in which regulated variable current control is provided. The lighting current control may be provided according to example circuits as shown in FIGS. **2-3**. The current control described herein may provide a lighting response as shown in FIG. **4**. The lighting system may be operated according to the method of FIG. **5**. Electrical interconnections shown between components in the various electrical diagrams represent current paths between the illustrate devices.

Referring now to FIG. **1**, a block diagram of a photoreactive system **10** in accordance with the system and method described herein is shown. In this example, the photoreactive system **10** comprises a lighting subsystem **100**, a controller **108**, a power source **102** and a cooling subsystem **18**.

The lighting subsystem **100** may comprise a plurality of light emitting devices **110**. Light emitting devices **110** may be LED devices, for example. Selected of the plurality of light emitting devices **110** are implemented to provide radiant output **24**. The radiant output **24** is directed to a work piece **26**. Returned radiation **28** may be directed back to the lighting subsystem **100** from the work piece **26** (e.g., via reflection of the radiant output **24**).

The radiant output **24** may be directed to the work piece **26** via coupling optics **30**. The coupling optics **30**, if used, may be variously implemented. As an example, the coupling optics may include one or more layers, materials or other structure interposed between the light emitting devices **110** providing radiant output **24** and the work piece **26**. As an example, the coupling optics **30** may include a micro-lens array to enhance collection, condensing, collimation or otherwise the quality or effective quantity of the radiant output **24**. As another example, the coupling optics **30** may include a micro-reflector array. In employing such micro-reflector array, each semiconductor device providing radiant output **24** may be disposed in a respective micro-reflector, on a one-to-one basis.

Each of the layers, materials or other structure may have a selected index of refraction. By properly selecting each index of refraction, reflection at interfaces between layers, materials and other structure in the path of the radiant output **24** (and/or returned radiation **28**) may be selectively controlled. As an example, by controlling differences in such indexes of refraction at a selected interface disposed between the semiconductor devices to the work piece **26**, reflection at that interface may be reduced, eliminated, or minimized, so as to enhance the transmission of radiant output at that interface for ultimate delivery to the work piece **26**.

The coupling optics **30** may be employed for various purposes. Example purposes include, among others, to protect the light emitting devices **110**, to retain cooling fluid associated with the cooling subsystem **18**, to collect, condense and/or collimate the radiant output **24**, to collect, direct or reject returned radiation **28**, or for other purposes, alone or in combination. As a further example, the photoreactive system **10** may employ coupling optics **30** so as to enhance the effective quality or quantity of the radiant output **24**, particularly as delivered to the work piece **26**.

Selected of the plurality of light emitting devices **110** may be coupled to the controller **108** via coupling electronics **22**, so as to provide data to the controller **108**. As described further below, the controller **108** may also be implemented to control such data-providing semiconductor devices, e.g., via the coupling electronics **22**.

The controller **108** preferably is also connected to, and is implemented to control, each of the power source **102** and the cooling subsystem **18**. Moreover, the controller **108** may receive data from power source **102** and cooling subsystem **18**.

The data received by the controller **108** from one or more of the power source **102**, the cooling subsystem **18**, the lighting subsystem **100** may be of various types. As an example, the data may be representative of one or more characteristics associated with coupled semiconductor devices **110**, respectively. As another example, the data may be representative of one or more characteristics associated with the respective component **12**, **102**, **18** providing the data. As still another example, the data may be representative of one or more characteristics associated with the work piece **26** (e.g., representative of the radiant output energy or spectral component(s) directed to the work piece). Moreover, the data may be representative of some combination of these characteristics.

The controller **108**, in receipt of any such data, may be implemented to respond to that data. For example, responsive to such data from any such component, the controller **108** may be implemented to control one or more of the power source **102**, cooling subsystem **18**, and lighting subsystem **100** (including one or more such coupled semiconductor devices). As an example, responsive to data from the lighting subsystem indicating that the light energy is insufficient at one or more points associated with the work piece, the controller **108** may be implemented to either (a) increase the power source's supply of current and/or voltage to one or more of the semiconductor devices **110**, (b) increase cooling of the lighting subsystem via the cooling subsystem **18** (i.e., certain light emitting devices, if cooled, provide greater radiant output), (c) increase the time during which the power is supplied to such devices, or (d) a combination of the above.

Individual semiconductor devices **110** (e.g., LED devices) of the lighting subsystem **100** may be controlled independently by controller **108**. For example, controller **108** may control a first group of one or more individual LED devices to emit light of a first intensity, wavelength, and the like, while controlling a second group of one or more individual LED devices to emit light of a different intensity, wavelength, and the like. The first group of one or more individual LED devices may be within the same array of semiconductor devices **110**, or may be from more than one array of semiconductor devices **110**. Arrays of semiconductor devices **110** may also be controlled independently by controller **108** from other arrays of semiconductor devices **110** in lighting subsystem **100** by controller **108**. For example, the semiconductor devices of a first array may be controlled to emit light of a first intensity, wavelength, and the like, while those of a second array may be controlled to emit light of a second intensity, wavelength, and the like.

As a further example, under a first set of conditions (e.g. for a specific work piece, photoreaction, and/or set of operating conditions) controller **108** may operate photoreactive system **10** to implement a first control strategy, whereas under a second set of conditions (e.g. for a specific work piece, photoreaction, and/or set of operating conditions) controller **108** may operate photoreactive system **10** to implement a second control strategy. As described above, the first control strategy may include operating a first group of one or more individual semiconductor devices (e.g., LED devices) to emit light of a first intensity, wavelength, and the like, while the second control strategy may include operating a second group of one or more individual LED devices to emit light of a second intensity, wavelength, and the like. The first group of LED devices may be the same group of LED devices as the second group, and may span one or more arrays of LED devices, or may be a different group of LED devices from the second group, and the different group of LED devices may include a subset of one or more LED devices from the second group.

The cooling subsystem **18** is implemented to manage the thermal behavior of the lighting subsystem **100**. For example, generally, the cooling subsystem **18** provides for cooling of such subsystem **12** and, more specifically, the semiconductor devices **110**. The cooling subsystem **18** may also be implemented to cool the work piece **26** and/or the space between the piece **26** and the photoreactive system **10** (e.g., particularly, the lighting subsystem **100**). For example, cooling subsystem **18** may be an air or other fluid (e.g., water) cooling system.

The photoreactive system **10** may be used for various applications. Examples include, without limitation, curing applications ranging from ink printing to the fabrication of DVDs and lithography. Generally, the applications in which the photoreactive system **10** is employed have associated parameters. That is, an application may include associated operating parameters as follows: provision of one or more levels of radiant power, at one or more wavelengths, applied over one or more periods of time. In order to properly accomplish the photoreaction associated with the application, optical power may need to be delivered at or near the work piece at or above a one or more predetermined levels of one or a plurality of these parameters (and/or for a certain time, times or range of times).

In order to follow an intended application's parameters, the semiconductor devices **110** providing radiant output **24** may be operated in accordance with various characteristics associated with the application's parameters, e.g., temperature, spectral distribution and radiant power. At the same time, the semiconductor devices **110** may have certain operating specifications, which may be are associated with the semiconductor devices' fabrication and, among other things, may be followed in order to preclude destruction and/or forestall degradation of the devices. Other components of the photoreactive system **10** may also have associated operating specifications. These specifications may include ranges (e.g., maximum and minimum) for operating temperatures and applied, electrical power, among other parameter specifications.

Accordingly, the photoreactive system **10** supports monitoring of the application's parameters. In addition, the photoreactive system **10** may provide for monitoring of semiconductor devices **110**, including their respective characteristics and specifications. Moreover, the photoreactive system **10** may also provide for monitoring of selected other components of the photoreactive system **10**, including their respective characteristics and specifications.

Providing such monitoring may enable verification of the system's proper operation so that operation of photoreactive system **10** may be reliably evaluated. For example, the system **10** may be operating in an undesirable way with respect to one or more of the application's parameters (e.g., temperature, radiant power, etc.), any components characteristics associated with such parameters and/or any component's respective operating specifications. The provision of monitoring may be responsive and carried out in accordance with the data received by controller **108** by one or more of the system's components.

Monitoring may also support control of the system's operation. For example, a control strategy may be implemented via the controller **108** receiving and being responsive to data from one or more system components. This control, as described above, may be implemented directly (e.g., by controlling a component through control signals directed to the component, based on data respecting that components operation) or indirectly (e.g., by controlling a component's operation through control signals directed to adjust operation of other components). As an example, a semiconductor device's radiant output may be adjusted indirectly through control signals directed to the power source **102** that adjust power applied to the lighting subsystem **100** and/or through control signals directed to the cooling subsystem **18** that adjust cooling applied to the lighting subsystem **100**.

Control strategies may be employed to enable and/or enhance the system's proper operation and/or performance of the application. In a more specific example, control may also be employed to enable and/or enhance balance between the array's radiant output and its operating temperature, so as, e.g., to preclude heating the semiconductor devices **110** or array of semiconductor devices **110** beyond their specifications while also directing radiant energy to the work piece **26** sufficient to properly complete the photoreaction(s) of the application.

In some applications, high radiant power may be delivered to the work piece **26**. Accordingly, the subsystem **12** may be implemented using an array of light emitting semiconductor devices **110**. For example, the subsystem **12** may be implemented using a high-density, light emitting diode (LED) array. Although LED arrays may be used and are described in detail herein, it is understood that the semiconductor devices **110**, and array(s) of same, may be implemented using other light emitting technologies without departing from the principles of the description, examples of other light emitting technologies include, without limitation, organic LEDs, laser diodes, other semiconductor lasers.

The plurality of semiconductor devices **110** may be provided in the form of an array **20**, or an array of arrays. The array **20** may be implemented so that one or more, or most of the semiconductor devices **110** are configured to provide radiant output. At the same time, however, one or more of the array's semiconductor devices **110** are implemented so as to provide for monitoring selected of the array's characteristics. The monitoring devices **36** may be selected from among the devices in the array **20** and, for example, may have the same structure as the other, emitting devices. For example, the difference between emitting and monitoring may be determined by the coupling electronics **22** associated with the particular semiconductor device (e.g., in a basic form, an LED array may have monitoring LEDs where the coupling electronics provides a reverse current, and emitting LEDs where the coupling electronics provides a forward current).

Furthermore, based on coupling electronics, selected of the semiconductor devices in the array **20** may be either/both multifunction devices and/or multimode devices, where (a) multifunction devices are capable of detecting more than one characteristic (e.g., either radiant output, temperature, magnetic fields, vibration, pressure, acceleration, and other mechanical forces or deformations) and may be switched among these detection functions in accordance with the application parameters or other determinative factors and (b) multimode devices are capable of emission, detection and some other mode (e.g., off) and are switched among modes in accordance with the application parameters or other determinative factors.

Referring to FIG. **2**, a schematic of a first lighting system circuit that may supply varying amounts of current is shown. Lighting system **100** includes one or more light emitting devices **110**. In this example, light emitting devices **110** are light emitting diodes (LEDs). Each LED **110** includes an anode **201** and a cathode **202**. Switching power source **102** shown in FIG. **1** supplies 48V DC power to voltage regulator **204** via path or conductor **264**. Voltage regulator **204** supplies DC power to the anodes **201** of LEDs **110** via conductor or path **242**. Voltage regulator **204** is also electrically coupled to cathodes **202** of LEDs **110** via conductor or path **240**. Voltage regulator **204** is shown referenced to ground **260** and may be a buck regulator in one example. Controller **108** is shown in electrical communication with voltage regulator **204**. In other examples, discrete input generating devices (e.g., switches) may replace controller **108**, if desired. Controller **108** includes central processing unit **290** for executing instructions. Controller **108** also includes inputs and outputs (I/O) **288** for operating voltage regulator **204** and other devices. Non-transitory executable instructions may be stored in read only memory **292** (e.g., non-transitory memory) while variables may be stored in random access memory **294**. Voltage regulator **204** supplies an adjustable voltage to LEDs **110**.

Variable resistor **220** in the form of a field-effect transistor (FET) receives an intensity signal voltage from controller **108** or via another input device. While the present example describes the variable resistor as an FET, one must note that the circuit may employ other forms of variable resistors.

In this example, at least one element of array **20** includes solid-state light-emitting elements such as light-emitting diodes (LEDs) or laser diodes produce light. The elements may be configured as a single array on a substrate, multiple arrays on a substrate, several arrays either single or multiple on several substrates connected together, etc. In one example, the array of light-emitting elements may consist of a Silicon Light Matrix™ (SLM) manufactured by Phoseon Technology, Inc.

The circuit shown in FIG. **2** is a closed loop current control circuit **208**. In closed loop circuit **208**, the variable resistor **220** receives an intensity voltage control signal via conductor or path **230** through the drive circuit **222**. The variable resistor **220** receives its drive signal from the driver **222**. Voltage between variable resistor **220** and array **20** is controlled to a desired voltage as determined by voltage regulator **204**. The desired voltage value may be supplied by controller **108** or another device, and voltage regulator **204** controls voltage signal **242** to a level that provides the desired voltage in a current path between array **20** and variable resistor **220**. Variable resistor **220** controls current flow from array **20** to current sense resistor **255** in the direction of arrow **245**. The desired voltage may also be adjusted responsive to the type of lighting device, type of work piece, curing parameters, and various other operating conditions. An electrical current signal may be fed back along conductor or path **236** to controller **108** or another device that adjusts the intensity voltage control signal provided to drive circuit **222** responsive to current feedback provided by path **236**. In particular, if the electrical current signal is different from a desired electrical current, the intensity voltage control signal passed via conductor **230** is increased or decreased to adjust electrical current through array **20**. A feedback current signal indicative of electrical current flow through array **20** is directed via conductor **236** as a voltage level that changes as electrical current flowing through current sense resistor **255** changes.

In one example where the voltage between variable resistor **220** and array **20** is adjusted to a constant voltage, current flow through array **20** and variable resistor **220** is adjusted via adjusting the resistance of variable resistor **220**. Thus, a voltage signal carried along conductor **240** from the variable resistor **220** does not go to the array **20** in this example. Instead, the voltage feedback between array **20** and variable resistor **220** follows conductor **240** and goes to a voltage regulator **204**. The voltage regulator **204** then outputs a voltage signal **242** to the array **20**. Consequently, voltage regulator **204** adjusts its output voltage in response to a voltage downstream of array **20**, and current flow through array **20** is adjusted via variable resistor **220**. Controller **108** may include instructions to adjust a resistance value of variable resistor **220** in response to array current fed back as a voltage via conductor **236**. Conductor **240** allows electrical communication between the cathodes **202** of LEDs **110**, input **299** (e.g., a drain of an N-channel MOSFET) of variable resistor **220**, and voltage feedback input **293** of voltage regulator **204**. Thus, the cathodes **202** of LEDs **110**, an input side **299** of variable resistor **220**, and voltage feedback input **293** are at the same voltage potential.

The variable resistor may take the form of an FET, a bipolar transistor, a digital potentiometer or any electrically controllable, current limiting device. The drive circuit may take different forms depending upon the variable resistor used. The closed loop system operates such that an output voltage regulator **204** remains about 0.5 V above a voltage to operate array **20**. The regulator output voltage adjusts voltage applied to array **20** and the variable resistor controls current flow through array **20** to a desired level. The present circuit may increase lighting system efficiency and reduce heat generated by the lighting system as compared to other approaches. In the example of FIG. **2**, the variable resistor **220** typically produces a voltage drop in the range of 0.6V. However, the voltage drop at variable resistor **220** may be less or greater than 0.6V depending on the variable resistor's design.

Thus, the circuit shown in FIG. **2** provides voltage feedback to a voltage regulator to control the voltage drop across array **20**. For example, since operation of array **20** results in a voltage drop across array **20**, voltage output by voltage regulator **204** is the desired voltage between array **20** and variable resistor **220** plus the voltage drop across array **220**. If the resistance of variable resistor **220** is increased to decrease current flow through array **20**, the voltage regulator output is adjusted (e.g., decreased) to maintain the desired voltage between array **20** and variable resistor **20**. On the other hand, if the resistance of variable resistor **220** is decreased to increase current flow through array **20**, the voltage regulator output is adjusted (e.g., increased) to maintain the desired voltage between array **20** and variable resistor **20**. In this way, the voltage across array **20** and current through array **20** may be simultaneously adjusted to provide a desired light intensity output from array **20**. In this example, current flow through array **20** is adjusted via a device (e.g., variable resistor **220**) located or positioned downstream of array **20** (e.g., in the direction of current flow) and upstream of a ground reference **260**.

In this example, array **20** is shown were all LEDs are supplied power together. However, current through different groups of LEDs may be controlled separately via adding additional variable resistors **220** (e.g., one for each array that is supplied controlled current). Controller **108** adjusts current through each variable resistor to control current through multiple arrays similar to array **20**.

Referring now to FIG. **3**, a schematic of a second lighting system circuit that may be supplied varying amounts of current is shown. FIG. **3** includes some of the same elements as the first lighting system circuit shown in FIG. **2**. Elements in FIG. **3** that are the same as elements in FIG. **2** are labeled with the same numeric identifiers. For the sake of brevity, a description of same elements between FIG. **2** and FIG. **3** is omitted; however, the description of elements in FIG. **2** applies to the elements in FIG. **3** that have the same numerical identifiers.

The lighting system shown in FIG. **3** includes a SLM section **301** that includes array **20** which includes LEDs **110**. The SLM also includes switch **308** and current sense resistor **255**. However, switch **308** and current sense resistor may be included with voltage regulator **304** or as part of controller **108** if desired. Voltage regulator **304** includes voltage divider **310** which is comprised of resistor **313** and resistor **315**. Conductor **340** puts voltage divider **310** into electrical communication with cathodes **202** of LEDs **110** and switch **308**. Thus, the cathodes **202** of LEDs **110**, an input side **305** (e.g., a drain of a N channel MOSFET) of switch **308**, and node **321** between resistors **313** and **315** are at a same voltage potential. Switch **308** is operated in only open or closed states, and it does not operate as a variable resistor having a resistance that can be linearly or proportionately adjusted. Further, in one example, switch **308** has a Vds of 0 V as compared to 0.6V Vds for variable resistor **220** shown in FIG. **2**.

The lighting system circuit of FIG. **3** also includes an error amplifier **326** receiving a voltage that is indicative of current passing through array **20** via conductor **340** as measured by current sense resistor **255**. Error amplifier **326** also receives a reference voltage from controller **108** or another device via conductor **319**. Output from error amplifier **326** is supplied to the input of pulse width modulator (PWM) **328**. Output from PWM is supplied to buck stage regulator **330**, and buck stage regulator **330** adjusts current supplied between a regulated DC power supply (e.g., **102** of FIG. **1**) and array **20** from a position upstream of array **20**.

In some examples, it may be desirable to adjust current to array via a device located or upstream (e.g., in the direction of current flow) of array **20** instead of a position that is downstream of array **20** as is shown in FIG. **2**. In the example lighting system of FIG. **3**, a voltage the feedback signal supplied via conductor **340** goes directly to voltage regulator **304**. A current demand, which may be in the form of an intensity voltage control signal, is supplied via conductor **319** from controller **108**. The signal becomes a reference signal Vref, and it is applied to error amplifier **326** rather than to the drive circuit for a variable resistor.

The voltage regulator **304** directly controls the SLM current from a position upstream of array **20**. In particular, resistor divider network **310** causes the buck regulator stage **330** to operate as a traditional buck regulator that monitors the output voltage of buck regulator stage **330** when the SLM is disabled by opening switch **308**. The SLM may selectively receive an enable signal from conductor **302** which closes switch **308** and activates the SLM to provide light. Buck regulator stage **330** operates differently when a SLM enable signal is applied to conductor **302**. Specifically, unlike more typical buck regulators, the buck regulator controls the load current, the current to the SLM and how much current is pushed through the SLM. In particular, when switch **308** is closed, current through array **20** is determined based on voltage that develops at node **321**.

The voltage at node **321** is based on the current flowing through current sense resistor **255** and current flow in voltage divider **310**. Thus, the voltage at node **321** is representative of current flowing through array **20**. A voltage representing SLM current is compared to a reference voltage provided by controller **108** via conductor **319** that represents a desired current flow through the SLM. If the SLM current is different from the desired SLM current, an error voltage develops at the output of error amplifier **326**. The error voltage adjusts a duty cycle of PWM generator **328** and a pulse train from PWM generator **328** controls a charging time and a discharging time of a coil within buck stage **330**. The coil charging and discharging timing adjusts an output voltage of voltage regulator **304**. Current flow through array **20** may be adjusted via adjusting the voltage output from voltage regulator **304** and supplied to array **20**. If additional array current is desired, voltage output from voltage regulator **304** is increased. If reduced array current is desired, voltage output from voltage regulator **304** is decreased.

Thus, the system of FIGS. **1-3** provides for a system for operating one or more light emitting devices, comprising: a voltage regulator including a feedback input, the voltage regulator in electrical communication with the one or more light emitting devices; and a controller including non-transitory instructions to provide a dampened current to the one or more light emitting devices in response to a requested step increase in output of the one or more light emitting devices. The system includes where the dampened current profile is based on a time for the one or more light emitting devices to reach half way to an irradiance output of the one or more light emitting devices at a steady state temperature of the light emitting devices.

The system also includes where the dampened current profile is based on a curvature that specifies a rate that irradiance of the one or more light emitting devices converges to a steady state value. The system includes where the dampened current profile is based on a current when the one or more light emitting devices is at a thermally steady state junction temperature. The system includes additional instructions to adjust a variable resister to provide the dampened current profile, and further comprising additional instructions to amplify current (e.g., increase to a value greater than the selected current I_{eq}) to the one or more light emitting devices in response to a requested step decrease in output of the one or more light emitting devices. The system includes additional instructions to output a voltage that corresponds to the dampened current response.

Referring now to FIG. **4**, a plot of an example simulated response of a lighting system is shown. The plot of FIG. **4** includes a first Y axis on the left side of the plot and a second Y axis on the right side of the plot. The first Y axis represents normalized irradiance and the second Y axis represents LED junction temperature. The X axis represents time and time increases from the left side of the plot to the right side of the plot. Time begins at time T**0** and increases to the rights side of the X axis. The lighting output of the array reaches a steady state value at time T**2** when the method of FIG. **5** is not used to control lighting array output.

The plot includes three curves **402-406**. Curve **402** represents irradiance of array **20** responsive to a step change in requested lighting array output when lighting array current is controlled according to the method of FIG. **5**. Curve **404** represents irradiance of array **20** responsive to a step change in requested lighting array output, the same step change in requested lighting array output as for curve **402**, when power is applied to array **20** without current control according to the method of FIG. **5**. Finally, curve **406** represents LED junction temperature for array **20** responsive to the same step change in requested lighting array output as for curve **402**. The step change in requested lighting array output begins at time T**0**.

It may be observed that curve **402** closely follows the step change in requested lighting array output. However, curve **404** shows that lighting array irradiance initially overshoots the desired output (e.g., the value of 1) and then decays to the desired output as the LED junction temperature increases. Consequently, the lighting array output may be greater than is desired in response to a request to increase lighting array output when lighting array current is not controlled according to the method of FIG. **5**. Thus, if a voltage and/or current are simply increased in response to a request for additional lighting array output, lighting array output may exceed a desired level when the method of FIG. **5** is not employed.

The time for the lighting array output to reach half way to the steady state temperature lighting irradiance output from the onset of the request to increase lighting array intensity (e.g., T**0**) when the method of FIG. **5** is not used to control array current is the amount of time between vertical markers T**0** and T**1**. This amount of time may be may be denoted as $t_{1/2max}$. An exponential rate of decay for the lighting array output to reach steady state from the onset of the request to increase lighting array intensity when the method of FIG. **5** is not used to control array current is referred to as the curvature and it may be by the exponential parameter denoted c. The parameter c describes the rate of decay at **420** for curve **404**.

Thus, FIG. **4** shows that the method of FIG. **5** allows a more uniform change in light array output in response to a request to increase lighting array output. The method of FIG. **5** provides a near step in irradiance output in response to a step change in desired lighting array output.

Referring now to FIG. **5**, a method for controlling output of a lighting system is shown. The method of FIG. **5** may be applied to a system as shown in FIGS. **1-4**. The method may be stored as executable instructions in non-transitory memory of a controller. Further, the method of FIG. **5** may operate a lighting array as shown in FIG. **4**.

At **502**, method **500** judges if LEDs are presently being commanded on or if LEDs are already activated. In one example, method **500** may judge if LEDs are being commanded on or already active in response to a controller input. The controller input may interface with a pushbutton or operator control. The controller input may be at a value of one if the LEDs are being commanded on or if the LEDs are already activated. If method **500** judges that LEDs are being commanded on, or if the LEDs are already on, the answer is yes and method **500** proceeds to **504**. Otherwise, the answer is no and method **500** proceeds to exit.

At **504**, method **500** judges whether or not LEDs are commanded to full power from an off state. In one example, method **500** judges if the LEDs are commanded to full power based on the irradiance or illuminance requested (e.g., from 0 to 100% power) and a previous value of requested irradiance or illuminance. If the requested irradiance or illuminance changes from zero to one hundred percent, the answer is yes and method **500** proceeds to **506**. Otherwise, the answer is no and method **500** proceeds to **520**.

At **506**, method **500** determines a time for the lighting array to reach one half of the final steady state temperature when the lighting array is operated at full light intensity (e.g., full power). The variable may be denoted as $t_{1/2max}$. In one example, the time is empirically determined and stored to a table or function in memory. Method **500** retrieves the time for the lighting array to reach one half of the final steady state temperature and proceeds to **508**.

At **508**, method **500** determines an initial dampening of the lighting array irradiance. The dampening parameter may be denoted as d_0. The dampening parameter may be empirically determined and stored to memory. The initial dampening may be determined by dividing the initial light output irradiance by the predicted steady state light output irradiance. For example, if the lamp emits 10% higher light output when it is first turned on (relative to steady state), then the eighty percent d_0 is given by: $d_0(80\%)=0.8/0.9$ where $d_0(100\%)=0.9$. Method **500** retrieves the dampening parameter and proceeds to **510**.

At **510**, method **500** looks up the curvature for the lighting array irradiance converging to steady state irradiance at the requested lighting intensity from memory. The curvature may be empirically determined and stored to memory. In one example, the curvature c is experimentally determined via adjusting the c parameter in the equation of step **514** such that the lighting array current causes the lighting array output to approach a step response. The value of c is typically in a range of 1 to 2.5. Method **500** retrieves the curvature value from memory and proceeds to **512**.

At **512**, method **500** determines lighting array current when the lighting array is supplied full power and operating at a thermal steady state condition. The lighting array current may be empirically determined and stored to memory. Method **500** retrieves the lighting array current at thermal steady state conditions and proceeds to **514**.

At **514**, method **500** adjusts or supplies current to the lighting array as a function of time since the LEDs were commanded fully on using current dampening for increasing lighting output. In one example, method **500** determines lighting array output from the following equation:

$$I(t) = \frac{\left(\frac{t}{t_{1/2max}}\right)^c + d_0}{\left(\frac{t}{t_{1/2max}}\right)^c + 1} \times I_{eq}$$

Where t is time since the request to increase lighting array intensity output and t starts at zero unless the lighting array is already outputting light, $t_{1/2max}$ is time for the lighting array output to reach half way to the steady state temperature lighting irradiance output from the onset of the request to increase lighting array intensity output, d_0 is an initial dampening value, c is a curvature value indicating the rate at which light intensity output converges to the new steady state value requested, I_{eq} is lighting array current at thermal steady state conditions, and I(t) is lighting array current as a function of time. Method **500** outputs a current command based on I(t) after a request to increase lighting array output. In some examples, the current command may be transformed via a transfer function to a voltage that represents a requested lighting array current via a transfer function that describes lighting array current as a function of an output voltage applied to the lighting array current sources described in FIGS. **2** and **3**. In this way, method **500** outputs a dampened current profile in response to a step request in lighting array output.

The current I_{eq} is lighting array current at thermal steady state conditions and it may be empirically determined and stored in a table or function that is indexed by desired lighting array output. The desired lighting array output may be specified based on electrical power supplied to the lighting array, irradiance, or illuminance. A step change in the desired lighting array output indexes the table or function and the table or function outputs current I_{eq}. Method **500** outputs current to the lighting array and proceeds to exit.

At **520**, method **500** judges whether or not a step increase in lighting array irradiance or illuminance is requested. In one example, method **500** judges if the LEDs are commanded to a step increase in output based on the irradiance or illuminance requested (e.g., from 30% to 60% power) and a previous value of requested irradiance or illuminance. If the requested irradiance or illuminance changes positively by more than a threshold amount, the answer is yes and method **500** proceeds to **522**. Otherwise, the answer is no and method **500** proceeds to **540**.

At **522**, method **500** adjusts a starting value of time t for the equation of step **514** based on the lighting array output before the present requested change in lighting array output. For example, if there is a requested change in lighting array output from 50% of full power to 80% of full power $t=2*t_{1/2max}*0.5$. In this way, the starting value of t may be updated to adjust the lighting array commanded current when the lighting array is already outputting light energy. Method **500** adjusts the starting value of time t and proceeds to **524**.

At **524**, method **500** adjusts the dampening parameter d_0 based on the final light intensity requested. In particular, the value of d_0 for full lighting array output is adjusted based on the fractional amount of lighting array output requested. For example, if lighting array output is request to be 80% of full irradiance or illuminance, the value of d_0 determined at **508** is adjusted as follows: $d_0(80\%)=1-((1-d_0(100\%))*0.8$. In this way, the dampening parameter is adjusted when an increase in lighting array output is requested. Method **500** retrieves the dampening parameter and proceeds to **526**.

At **526**, method **500** looks up the curvature for the lighting array irradiance converging to steady state irradiance at the requested lighting intensity from memory. The curvature may be empirically determined and stored to memory. The curvature may be determined as described at step **510**. Method **500** retrieves the curvature value from memory and proceeds to **528**.

At **528**, method **500** determines lighting array current when the lighting array is supplied full power and operating at a thermal steady state condition. The lighting array current may be empirically determined and stored to memory. Method **500** retrieves the lighting array current at thermal steady state conditions and proceeds to **530**.

At **530**, method **500** adjusts or supplies current to the lighting array as a function of time since the LEDs were commanded to a new irradiance or illuminance using current dampening for increasing lighting output. In one example, method **500** determines lighting array output from the equation described in step **514**. Method **500** outputs a current command based on I(t) after a request to increase lighting array output. The current command may be transformed via a transfer function to a voltage that represents a requested lighting array current via a transfer function that describes lighting array current as a function of an output voltage applied to the lighting array current sources described in FIGS. **2** and **3**. In this way, method **500** outputs a dampened current profile in response to a step request in lighting array output. Method **500** outputs the lighting array current and proceeds to exit.

At **540**, method **500** judges whether or not a step decrease in lighting array irradiance or illuminance is requested. In one example, method **500** judges if the LEDs are commanded to a step decrease in output based on the irradiance or illuminance requested (e.g., from 80% to 50% power) and a previous value of requested irradiance or illuminance. If the requested irradiance or illuminance changes negatively by more than a threshold amount, the answer is yes and method **500** proceeds to **542**. Otherwise, the answer is no and method **500** proceeds to **560**.

At **542**, method **500** adjusts a starting value of time t for the equation of step **550** based on the lighting array output before the present requested change in lighting array output. For example, if there is a requested change in lighting array output from 80% of full power to 50% of full power $t=2*t_{1/2max}*0.8$. In this way, the starting value of t may be updated to adjust the lighting array commanded current when the lighting array is already outputting light energy. Method **500** adjusts the starting value of time t and proceeds to **544**.

At **544**, method **500** adjusts the dampening parameter d_0 based on the final light intensity requested. In particular, the value of d_0 for full lighting array output is adjusted based on the fractional amount of lighting array output requested. For example, if lighting array output is request to be 50% of full irradiance or illuminance starting from a value of 80%, the value of d_0 determined at **508** is adjusted as follows: $d_0(50\%)=1-((1-d_0(100\%))*0.5$. In this way, the dampening parameter is adjusted when a decrease in lighting array output is requested. Method **500** retrieves the dampening parameter and proceeds to **546**.

At **546**, method **500** looks up the curvature for the lighting array irradiance converging to steady state irradiance at the requested lighting intensity from memory. The curvature may be empirically determined and stored to memory. The curvature may be determined as described at step **510**. Method **500** retrieves the curvature value from memory and proceeds to **548**.

At **548**, method **500** determines lighting array current when the lighting array is supplied full power and operating at a thermal steady state condition. The lighting array current may be empirically determined and stored to memory. Method **500** retrieves the lighting array current at thermal steady state conditions and proceeds to **550**.

At **550**, method **500** adjusts or supplies current to the lighting array as a function of time since the LEDs were commanded to a new irradiance or illuminance using current amplification for decreasing lighting output. In one example, method **500** determines lighting array output from the following equation:

$$I(t) = \frac{\left(\frac{t}{t_{1/2max}}\right)^c + 1}{\left(\frac{t}{t_{1/2max}}\right)^c + d_0} \times I_{eq}$$

The variables for step **550** are the same variables as described in step **514**. Method **500** outputs a current command to control lighting array current based on I(t) after a request to decrease lighting array output is provided. The current command may be transformed via a transfer function to a voltage that represents a requested lighting array current via a transfer function that describes lighting array current as a function of an output voltage applied to the lighting array current sources described in FIGS. **2** and **3**. Current I_{eq} is amplified at step **550** to provide current I(t). In other words, drive current I(t) is amplified from I_{eq} (e.g., increased) in response to a decreasing step in requested irradiance. In this way, method **500** outputs an amplified current profile in response to a decreasing step request in lighting array output. Method **500** proceeds to exit after the lighting array current is output.

At **560**, method **500** continues to supply current based on the previously requested change in irradiance or illuminance so that current supplied to the lighting array converges to the current at thermal steady state conditions. Thus, the method of FIG. **5** continues to control current supplied to the lighting array via the equation described at **514** or the equation described at **550** depending on the whether the lighting output is increased or decreased in a step-wise manner.

In this way, the method of FIG. **5** provides for a method for operating one or more light emitting devices, comprising: selecting a current that corresponds to a desired irradiance output of the one or more light emitting devices at thermal steady state conditions of the one or more light emitting devices in response to a step change in the desired irradiance output of the one or more light emitting devices; and dampening the current based on one or more irradiance response attributes of the one or more light emitting devices when the one or more light emitting devices respond to the step change in the desired irradiance output without dampening the current; and outputting the dampened current to the one or more light emitting devices. In other words, lighting response attributes determined by supplying a step increase or decrease in voltage or current supplied to the lighting array without dampening or amplifying (e.g., increasing) lighting array current may be subsequently applied to dampen or amplify lighting array current during a later activation of the lighting array.

In some examples, the method includes where the current is dampened based on a time for the one or more light emitting devices to reach one half of a steady state temperature light output corresponding to the current. The method includes where the current is dampened based on a curvature that specifies a rate that irradiance of the one or more light emitting devices converges to a steady state value. The method includes where the current is based on when the one or more light emitting devices is at a thermally steady state junction temperature at the desired irradiance output. The method includes where dampening the current includes adjusting the current according to a first equation in response to the step change in the desired irradiance increasing.

The method also includes where dampening the current includes adjusting the current according to a second equation in response to the step change in the desired irradiance decreasing. The method includes where the dampened current is provided via a variable resistor. The method includes where the dampened current is provided via a buck stage regulator.

The method of FIG. **5** also includes a method for operating one or more light emitting devices, comprising: in response to a step change in requested output of the one or more light emitting devices, adjusting current supplied to the one or more light emitting devices responsive to one or more parameters based on output of the one or more light emitting devices when a step change in voltage or current is applied to the one or more light emitting devices, the step change in voltage or current not occurring at a same time as the step change in the requested output of the one or more light emitting devices. The method includes where the one or more parameters includes a curvature parameter.

In some examples, the method includes where the one or more parameters includes a dampening parameter. The method includes where the step change is an increasing step change. The method includes where the step change is a decreasing step change. The method further comprises adjusting the current supplied to the one or more light emitting devices in response to initial conditions of the one or more light emitting devices, the initial conditions being other than zero.

As will be appreciated by one of ordinary skill in the art, the methods described in FIG. **5** may represent one or more of any number of processing strategies such as event-driven, interrupt-driven, multi-tasking, multi-threading, and the like. As such, various steps or functions illustrated may be performed in the sequence illustrated, in parallel, or in some cases omitted. Likewise, the order of processing is not necessarily required to achieve the objects, features, and advantages described herein, but is provided for ease of illustration and description. Although not explicitly illustrated, one of ordinary skill in the art will recognize that one or more of the illustrated steps or functions may be repeatedly performed depending on the particular strategy being used. Further, the described actions, operations, methods, and/or functions may graphically represent code to be programmed into non-transitory memory of the computer readable storage medium in the lighting control system.

This concludes the description. The reading of it by those skilled in the art would bring to mind many alterations and modifications without departing from the spirit and the scope of the description. For example, lighting sources producing different wavelengths of light may take advantage of the present description.

The invention claimed is:

1. A system for operating one or more light emitting devices, comprising:

a voltage regulator including a feedback input, the voltage regulator in electrical communication with the one or more light emitting devices; and

a controller including non-transitory instructions to provide a dampened current to the one or more light emitting devices in response to a requested step increase in output of the one or more light emitting devices, and where a dampened current profile is based on a curvature that specifies a rate that irradiance of the one or more light emitting devices converges to a steady state value.

2. The system of claim **1**, where the dampened current profile is based on a time for the one or more light emitting devices to reach half way to an irradiance output of the one or more light emitting devices at a steady state temperature of the light emitting devices.

3. The system of claim **1**, where the dampened current profile is based on a current when the one or more light emitting devices is at a thermally steady state junction temperature.

4. The system of claim **1**, including additional instructions to adjust a variable resistor to provide the dampened current, and further comprising additional instructions to amplify current to the one or more light emitting devices in response to a requested step decrease in output of the one or more light emitting devices.

5. The system of claim **1**, including additional instructions to output a voltage that corresponds to the dampened current.

6. A method for operating one or more light emitting devices, comprising:

selecting a current that corresponds to a desired irradiance output of the one or more light emitting devices at thermal steady state conditions of the one or more light emitting devices in response to a step increase in the desired irradiance output of the one or more light emitting devices;

dampening the current based on one or more irradiance response attributes of the one or more light emitting devices when the one or more light emitting devices respond to the step increase in the desired irradiance output without dampening the current; and

outputting the dampened current to the one or more light emitting devices.

7. The method of claim **6**, where the current is dampened based on a time for the one or more light emitting devices to reach one half of a steady state temperature light output corresponding to the current.

8. The method of claim **6**, where the current is dampened based on a curvature that specifies a rate that irradiance of the one or more light emitting devices converges to a steady state value.

9. The method of claim **6**, where the current is based on when the one or more light emitting devices is at a thermally steady state junction temperature at the desired irradiance output.

10. The method of claim **6**, where dampening the current includes adjusting the current according to a first equation in response to the step change in the desired irradiance increasing.

11. The method of claim **10**, where dampening the current includes adjusting the current according to a second equation in response to the step change in the desired irradiance decreasing.

12. The method of claim **6**, where the dampened current is provided via a variable resistor.

13. The method of claim **6**, where the dampened current is provided via a buck stage regulator.

14. A method for operating one or more light emitting devices, comprising:

in response to a step change in requested output of the one or more light emitting devices, adjusting current supplied to the one or more light emitting devices responsive to one or more parameters based on output of the one or more light emitting devices when a step change in voltage or current is applied to the one or more light emitting devices, the step change in voltage or current not occurring at a same time as the step change in the requested output of the one or more light emitting devices; and

adjusting the current supplied to the one or more light emitting devices in response to initial conditions of the one or more light emitting devices, the initial conditions being other than zero.

15. The method of claim **14**, where the one or more parameters includes a curvature parameter.

16. The method of claim **14**, where the one or more parameters includes a dampening parameter.

17. The method of claim **14**, where the step change is an increasing step change.

18. The method of claim **14**, where the step change is a decreasing step change.

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